THE UPPER ASYMPTOTIC GIANT BRANCH OF THE ELLIPTICAL GALAXY MAFFEI 1, AND COMPARISONS WITH M32 AND NGC 5128

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ABSTRACT

Deep near-infrared images obtained with adaptive optics (AO) systems on the Gemini North and Canada-France-Hawaii telescopes are used to investigate the bright stellar content and central regions of the nearby elliptical galaxy Maffei 1. Stars evolving on the upper asymptotic giant branch (AGB) are resolved in a field 3 arcmin from the center of the galaxy. The locus of bright giants on the $(K, H-K)$ color-magnitude diagram is consistent with a population of stars like those in Baade's Window reddened by $E(H-K) = 0.28 \pm 0.05$ mag. This corresponds to $A_V = 4.5 \pm 0.8$ mag, and is consistent with previous estimates of the line of sight extinction computed from the integrated properties of Maffei 1. The AGB-tip occurs at $K = 20.0$, which correponds to $M_K = -8.7$; hence, the AGB-tip brightness in Maffei 1 is comparable to that in M32, NGC 5128, and the bulges of M31 and the Milky-Way. The near-infrared luminosity functions (LFs) of bright AGB stars in Maffei 1, M32, and NGC 5128 are also in excellent agreement, both in terms of overall shape and the relative density of infrared-bright stars with respect to the fainter stars that dominate the light at visible and red wavelengths. It is concluded that the brightest AGB stars in Maffei 1, NGC 5128, M32, and the bulge of M31 trace an old,

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metal-rich population, rather than an intermediate age population. It is also demonstrated that Maffei 1 contains a distinct red nucleus, and this is likely the optical signature of low-level nuclear activity and/or a distinct central stellar population. Finally, there is an absence of globular clusters brighter than the peak of the globular cluster LF in the central 700 × 700 parsecs of Maffei 1.

Subject headings: galaxies: individual (Maffei 1, M32, NGC 5128) - galaxies: elliptical and lenticular - galaxies: evolution - galaxies: nuclei - stars: AGB

1. INTRODUCTION

The brightnesses and spatial distributions of stars evolving on the asymptotic giant branch (AGB) provide clues about the past evolution of galaxies. Although stars near the AGB-tip are relatively bright, efforts to resolve these objects in the dense main bodies of nearby spheroids typically require angular resolutions approaching the diffraction limit of 2.5-metre or larger telescopes. Spheroids within the Local Group are obvious first targets for any studies of resolved stellar content, and Davidge (2000a), Davidge et al. (2000), and Davidge (2001a) found that the brightest AGB stars in the compact elliptical galaxy M32 and the bulge of M31 have similar brightnesses, and are well mixed with the fainter stars in these systems. This suggests that the most luminous AGB stars in M32 and the bulge of M31 belong to a population that formed when the structural characteristics of these galaxies were imprinted (Davidge 2001a). A similar AGB population may be present in the bulge of the Milky-Way (Davidge 2001a) – a system that deep photometric studies indicate has an old age (Feltzing & Gilmore 2000; Ortolani et al. 1995).

Davidge (2001a) suggested that the bright AGB stars detected in Local Group spheroids trace an old, metal-rich population, and this suggestion can be tested by examining the brightness and spatial distribution of AGB stars in a larger sample of spheroids. With a distance between 4 and 4.5 Mpc (Davidge & van den Bergh 2001; Luppino & Tonry 1993), Maffei 1 is one of the closest large elliptical galaxies, and hence is an obvious target for efforts to study the bright stellar content. A complicating factor is that Maffei 1 is viewed through the Galactic disk, and so is subject to significant foreground extinction. Buta & McCall (1983) concluded that $A_V = 5.1 \pm 0.2$ based on the integrated color of Maffei 1 and the column density of hydrogen along the line of sight. Hence, efforts to resolve stars in Maffei 1 will likely be most successful in the near-infrared, which is also the prime wavelength regime for investigating stars on the upper AGB. Davidge & van den Bergh (2001; hereafter DvdB) investigated the near-infrared photometric properties of the brightest AGB stars in a field with a projected distance of 6 arcmin from the center of Maffei 1. Despite long integration times (3 hours per filter) and image quality close to the theoretical diffraction limit of the CFHT, only stars within ~ 1.5 mag of the AGB-tip were detected.

In the present study, two datasets are used to investigate different regions of Maffei 1. The first dataset consists of deep H and K' images obtained with the University of Hawaii Adaptive Optics (UHAO) system on the Gemini North telescope, which sample a field 3 arcmin from the center of Maffei 1. Not only is the stellar density higher than in the field studied by DvdB, but stars that are 1 mag in K fainter than in the DvdB dataset are detected, permitting a detailed comparison with the bright stellar contents of other galaxies.

The second dataset consists of J, H, and Ks images of the center of Maffei 1 that were obtained with the CFHT AO system. While not diffraction-limited, these data have a resolution that permits the central 700×700 parsecs of the galaxy to be investigated at sub-arcsec angular scales. Data of this nature can determine if Maffei 1 has a photometrically distinct nucleus, which in turn provides clues about the past evolution of this galaxy.

The paper is structured as follows. Details of the observations and the data reduction techniques are presented in §2, while the photometric properties of stars in the Gemini dataset are discussed and compared with those of other galaxies in §3 and 4. The photometric properties of the central regions of Maffei 1 are examined in §5, while the results of a search for globular clusters in both datasets is presented in §6. A summary and discussion of the results of this paper follows in §7.

2. OBSERVATIONS & REDUCTIONS

H and K' images of a field located $3'.2$ from the center of Maffei 1, which will be refered to as the 'deep' field throughout this paper, were recorded during the night of UT September 16 2001 with the UHAO system and QUIRC imager, which were mounted at the f/16 Cassegrain focus of the 8 metre Gemini North telescope. The detector in QUIRC is a 1024×1024 Hg:Cd:Te array, with each pixel subtending $0''.02$ on a side, so that a $20''.5 \times 20''.5$ field is imaged. A detailed description of the UHAO system has been given by Graves et al. (1998).

The UHAO system uses natural guide stars as reference sources to monitor wavefront distortion, and the guide star for these observations was the $R = 13.4$ star GSC 03699-01165 ($\alpha =$ 02:36:11, $\delta =$ +59:40:15 E2000). Data in K' were recorded at three pointings, with the guide star offset by $3''.5$ between each of these. While this offset is significant when compared with the QUIRC science field, and hence has a major impact on the angular extent of the final field, it was employed so that a calibration frame for removing interference fringes and thermal emission signatures could be constructed from these data alone. 5×60 sec exposures were recorded at the corners of a $2'' \times 2''$ square dither pattern for each pointing, and so the total exposure time in K' is 3 pointings $\times 4$ dither positions per pointing $\times$ 5 exposures per dither position $\times 60$ sec per exposure = 3600 seconds. Images in H were recorded using the same dither pattern and 60 sec exposure time, although data were recorded at only 2 pointings due to time restrictions, so that the total integration time in this filter is 2400 seconds (i.e. two thirds that in K').

The final images have FWHM = $0''.13$ (H) and $0''.14$ (K'), which are larger than the $\frac{\lambda}{D} = 0''.04(H)$ and $0''.06(K')$ telescope diffraction limits. These data thus have low Strehl ratios, due mainly to the seeing being slightly worse than the Mauna Kea median on this night, with an uncorrected FWHM $\sim 1''.0$ at visible wavelengths. The UHAO uses a 36 element wavefront sensor; while this is adequate to deliver diffraction-limited images at near-infrared wavelengths on a 4 metre telescope during median Mauna Kea seeing conditions, good seeing is required to achieve a high Strehl ratio with this order of compensation on an 8 metre telescope. Despite having low Strehl ratios, the angular resolution of these data is slightly better than was obtained by DvdB, who achieved FWHM = $0''.14$ in H and $0''.15$ in Ks.

Two standards from Hawarden et al. (2001) were observed on the same night that the Maffei 1 data were recorded. A growth curve analysis established that a $1''.5$ aperture contained, for all practical purposes, all of the light from these stars. The zeropoints predicted from the two standards differ by only 0.06 mag in K, and the mean zeropoint agrees to within 0.1 mag of that measured during previous UHAO + QUIRC observing runs (e.g. Davidge et al. 2000).

The center of Maffei 1 was observed with the CFHT AOB and KIR imager during the night of UT September 10 2000. The detector in KIR is a 1024×1024 Hg:Cd:Te array, with each pixel subtending $0''.034$ on a side, so that the total imaged field is $34''.8 \times 34''.8$. The CFHT AO system, which has been described by Rigaut et al. (1998), uses natural guide stars to monitor wavefront distortion, and the $R = 12.3$ star GSC 03699-01147, which is $0'.43$ from the center of Maffei 1, was used as the reference source for these observations. A single 60 sec exposure was recorded at each corner of a $1'' \times 1''$ square dither pattern through J, H, and Ks filters; the total integration time is thus $4 \times 60 = 240$ sec per filter.

Stars in the final CFHT images have FWHM = $0''.25$ in J, $0''.30$ in H, and $0''.35$ in Ks. The angular resolution is thus much larger than the theoretical diffraction limits of the

CFHT, which are $\frac{\lambda}{D} = 0\farcs07, 0\farcs09$, and $0\farcs12$ in J, H, and Ks. The low Strehl ratios of these data is due to poor natural seeing conditions when they were recorded. Nevertheless, these data still have an angular resolution that is superior to any previous observations of the center of Maffei 1 at these wavelengths.

Six standard stars were observed with the CFHT AOB + KIR on the nights of Sept 10 and 11 2000. The standard deviations in the photometric zeropoints are $\pm 0.03, \pm 0.02$, and ± 0.04 mag in J, H, and Ks. The photometric zeropoints computed from these data are consistent those derived on previous runs using the same instrumental configuration (e.g. Davidge & Courteau 1999a; Davidge et al. 2000).

The data reduction sequence for the raw images from both the CFHT and Gemini datasets was as follows: (1) dark subtraction, (2) division by a dome flat, (3) subtraction of a calibration frame to remove thermal artifacts and interference fringes, and (4) subtraction of the DC sky level at each dither position. The processed images in each filter were then registered, median-combined, and trimmed to the area having full integration time; the final images of the deep field thus cover $14\farcs6 \times 14\farcs4$, while those of the central field cover $34\farcs0 \times 34\farcs0$. The final K' and Ks images of the deep and central fields are shown in Figures 1 and 2. Individual stars in Maffei 1 are clearly evident in Figure 1.

3. THE MAFFEI 1 DEEP FIELD

3.1. Photometry of Stars in the Maffei 1 Deep Field

The brightnesses of stars in the deep field were measured with the PSF-fitting program ALLSTAR (Stetson & Harris 1988). Target lists, preliminary brightnesses, and PSFs were obtained using DAOPHOT (Stetson 1987) tasks. There are indications that the PSF is very uniform across the field, and this is demonstrated in Figure 3, where the mean K' light profiles of stars in two radial intervals, centered on the guide star and selected to sample roughly equal areas, are compared. The comparison in Figure 3 should be viewed with some caution, as FWHM is not an unambiguous estimator of Strehl ratio, while information about any radial elongation of stellar images in the direction of the guide source, which is a classical signature of anisoplanicity (e.g McClure et al. 1991), is largely lost when considering radially-averaged profiles of the type shown in this figure. Nevertheless, based on the uniformity evident in Figure 3, it was decided to construct a single PSF for each filter. The absence of obvious signatures of anisoplanicity is not surprising given previous experience with the CFHT AO system, which indicates that the PSF is stable over the $34\farcs8 \times 34\farcs8$ KIR science field for moderate orders of AO compensation during typical atmospheric conditions (e.g. Davidge & Courteau 1999a; Davidge 2001b). Not only does the Maffei 1 deep field, with dimensions of $14''.6 \times 14''.4$, cover a smaller area than the CFHT KIR field but, when used on an 8 metre telescope, the UHAO, which has a 36 element wave front sensor (WFS), delivers a lower order of correction than the 19 element WFS AO system used on the 3.6 meter CFHT, and this further contributes to PSF uniformity.

The photometric calibration was defined using the standard star observations discussed in §2, with the instrumental K' measurements being transformed into K magnitudes. Wainscoat & Cowie (1992) find that there is a significant color term between $K' - K$ and $H - K$. As only two standards were observed to calibrate the Maffei 1 deep field data, a relation between $K' - K$ and $H - K$ was derived from the entries in Table 1 of Wainscoat & Cowie (1992). While those authors chose to fit a linear relation to their data over the full range of colors, the entries in their Table 1 suggest that there is a break in the relation near $H - K = 0.4$, in the sense that $K - K' \sim 0.06$ when $H - K \geq 0.4$, and so the calibration of the deep field data assumes that $K - K' = 0.06$ for very red colors. The uncertainty in the transformation equation color term likely contributes ± 0.05 mag uncertainty to the Maffei 1 photometry.

The order of AO correction depends on factors such as atmospheric conditions and the brightness of the AO guide star, and for these reasons the standard stars likely have different Strehl ratios than the stars in the Maffei 1 deep field. To avoid complications introduced by such differences in Strehl ratio, the Maffei 1 data were calibrated using large radius aperture photometry of the PSF stars. All detected neighboring stars were removed from the deep field images prior to measuring the brightnesses of the PSF stars, and the aperture size was set at the same large radius as the standard star measurements. This same calibration procedure has been used in previous studies with the CFHT AO system, and it has been demonstrated to produce consistent brightnesses from data obtained during different runs (Davidge & Courteau 2002), and with different guide stars (Davidge 2001b). Hence, the calibration procedure is insensitive to differences in Strehl ratio. This robust calibration procedure was also employed for studies of the brightest stars in M32 (Davidge 2000; Davidge et al, 2000) and the bulge of M31 (Davidge 2001a) using the same instruments. The observations of Maffei 1, M32, and the bulge of M31 thus form a homogeneous dataset for comparing the bright stellar content of these systems.

Artificial star experiments, in which scaled versions of the PSF with noise were added to the images using the DAOPHOT ADDSTAR task, were run to assess completeness and the uncertainties in the photometric measurements due to crowding and photon noise. The artificial stars were assigned $H - K = 0.7$ to match the Maffei 1 stellar locus (§3.2) and $K > 19.5$. The artificial star experiments indicate that completeness drops from 100% at

$K = 20$ to 50% at $K = 22$.

3.2. The $(K, H - K)$ CMD and K LF of Stars in the Maffei 1 Deep Field

The $(K, H-K)$ CMD of the deep field is plotted in Figure 4, where the errorbars show the uncertainties predicted from the artificial star experiments. Giants in Maffei 1 form a broad plume when $K > 20$. The errorbars predicted by the artificial star experiments match the observed scatter in $H - K$ in the Maffei 1 giant branch, indicating that the spread in the data is due to photometric errors, rather than an intrinsic dispersion in stellar properties.

The peak brightness of the Maffei 1 CMD in Figure 4, which we identify as the AGB-tip, occurs at $K = 20$, and this is in excellent agreement with what was predicted by DvdB [3]. The mean color of stars with K between 20.0 and 21.5 in Figure 4 was computed using an iterative $2 - \sigma$ rejection threshold to suppress outliers, and the result is $\overline{H-K} = 0.71 \pm 0.02$, where the uncertainty is the formal error in the mean. This mean color is insensitive to the magnitude range from which it is computed, and is consistent with the location of the Maffei 1 sequence in the $(K, H - K)$ CMD shown in Figure 1 of DvdB.

The reddening towards the Maffei 1 deep field can be estimated if it is assumed that the brightest stars have the same intrinsic colors as M giants in Baade's Window (BW), the brightest of which have $(H - K)_0 \sim 0.43$ (Frogel & Whitford 1987). Since $\overline{H-K} = 0.71$, then the color excess of the Maffei 1 deep field is $E(H - K) \sim 0.28$. The dominant source of uncertainty in $E(H - K)$ is the photometric calibration, which has an estimated error of ± 0.05. The corresponding extinctions in K and V, computed using the Rieke & Lebofsky (1985) reddening curve, are $A_K \sim 0.5 \pm 0.1$ and $A_V \sim 4.5 \pm 0.8$. The extinction measured from the deep field CMD is thus not significantly different from that estimated by Buta & McCall (1983) using other techniques.

The adopted reddening affects the true distance modulus. Luppino & Tonry (1993) assumed $A_K = 0.63$ to get $\mu_0 = 28.1 \pm 0.25$ from surface brightness flucuations, whereas if $A_K = 0.5 \pm 0.1$, based on the color of stars in Maffei 1, then $\mu_0 = 28.2 \pm 0.25$. The latter distance modulus will be used for the remainder of the paper.

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[3]The low stellar density in the DvdB field, coupled with the modest science field of the KIR imager, resulted in a low probability of detecting AGB-tip stars. Based on the number density of objects at fainter magnitudes and star counts in M32 and the bulge of M31, DvdB predicted that the AGB-tip in Maffei 1 should occur near $K = 20.0 \pm 0.25$

The K LF of the deep field is shown in Figure 5. The completeness-corrected LF follows a power-law, with an apparent discontinuity between $K = 20$ and $K = 20.5$. The power-law exponent $x = \frac{dlog(n_{0.5})}{dK}$, computed from a least squares fit to the LF between $K = 20.25$ and 22.75, is 0.70 ± 0.07. The LF is therefore significantly different from that of first ascent giants in various bulge fields, where $x \sim 0.34$ (Davidge 2000b). The stars detected in Maffei 1 are intrinsically bright, and evolving on the AGB. Stars in the Galactic Bulge with the same intrinsic brightness as those in the Maffei 1 deep field have $K_0 < 8.1$; not only are such objects relatively rare, but they are usually saturated in imaging surveys of the Galactic Bulge. DePoy et al. (1993) examined the K LF of bright stars in BW. Their Figure 3 includes data not only from their survey, which suffers from saturation effects at the bright end, but also from Frogel & Whitford (1987) and Davidge (1991), and it is evident from the combined datasets in this figure that the K LF of BW appears to steepen (i.e. x will be significantly larger than the value measured from RGB stars) when $K_0 < 8$.

The RGB-tip in old solar metallicity populations occurs near $M_K^{RGBT} = -7$ (Bertelli et al. 1994), which corresponds to $K = 21.7$ in Maffei 1; therefore, the discontinuity at the bright end in Figure 5 is not due to the onset of the RGB. This being said, there is not a clear discontinuity near $K = 21.7$ in Figure 5. The absence of an RGB-tip feature in the LF is due in part to the metallicity-sensitive nature of M_K^{RGBT}. The stars in the deep field likely span a range of metallicities, and this will blur any discontinuity in the LF caused by the onset of the RGB. In addition, there are significant photometric errors near the faint limit of our data, and these further smear any signature of the RGB-tip.

4. COMPARISONS WITH THE DvdB FIELD, M32, AND NGC 5128

In this Section the bright AGB content of the Maffei 1 deep field is compared with the stellar contents in the outer regions of Maffei 1, M32, and NGC 5128 (Cen A). The latter is the closest large elliptical (e.g. Israel 1998, and references therein). These comparisons are based on the peak AGB brightness, the shape of the LF, and the number density of bright AGB stars, normalized using published surface brightness measurements.

The K LFs of the deep and DvdB fields are compared in the upper panel of Figure 6. These fields sample areas of Maffei 1 that have different stellar densities, and the LF of the DvdB field in Figure 6 was scaled along the vertical axis to match the stellar density in the deep field according to the $I-$band surface brightness profile of Buta & McCall (1999).

The LFs in the upper panel of Figure 6 agree within the estimated uncertainties at $K = 21.5$, which is near the expected onset of the RGB (§3). However, the K LF of the

DvdB field falls below that of the deep field along the upper AGB; the difference between the two LFs at $K = 21$ is significant at less than the $2 - \sigma$ level, but at $K = 20.5$ the difference is significant at almost the $3 - \sigma$ level. The comparison in Figure 6 thus suggests that the DvdB field may be deficient in the brightest evolved stars when compared with the deep field.

After accounting for differences in distance and stellar density, the bright stellar content in the Maffei 1 deep field is representative of that in other nearby elliptical galaxies. In the lower panel of Figure 6 the K LFs of the Maffei 1 deep field and the M32 outer field studied by Davidge (2000a) are compared. We assumed that M32 is equidistant with M31, for which a distance modulus $\mu_0 = 24.4$ was adopted (van den Bergh 2000), while $\mu_0 = 28.2$ and $A_K = 0.5$ were used for Maffei 1 (see above). The M32 LF was shifted along the vertical axis so that the stellar density matched that in the deep field based on the V-band surface brightness profile of Maffei 1 from Buta & McCall (1999) and the r-band surface brightness profile of M32 from Kent (1987); a correction was also applied for the difference in distance. The integrated color of Maffei 1 was assumed to be $V - r = 0.25$, which is typical for an elliptical galaxy (Frei & Gunn 1994).

While the M32 LF in Figure 6 falls consistently above the Maffei 1 LF, the mean difference is within the systematic uncertainties in the relative distances and reddenings of the two systems. Moreover, the peak brightnesses in these systems are similar; in M32 the AGB-tip occurs near $M_K = -8.9 \pm 0.1$, while in Maffei 1 $M_K = 20 - (28.2 + 0.5) = -8.7 \pm 0.1$. Thus, the bright stellar contents of the outer regions of M32 and the Maffei 1 deep field are not significantly different.

The M32 outer field studied by Davidge (2000a) samples a low density region of this galaxy where crowding is not an issue; hence, the M32 LF in Figure 6 can be used to estimate the number of blends in the Maffei 1 data if it is assumed that the outer regions of M32 and the Maffei 1 deep field have similar stellar contents. When shifted to match the distance and surface brightness of the Maffei 1 deep field, the M32 LF predicts that there should be 3.2 stars per 0.5 mag interval per arcsec^2 at $K = 22.5$. If each resolution element in the Maffei 1 data has a radius that is one half the FWHM, then this corresponds to 0.05 stars per 0.5 mag interval per resolution element at $K = 22.5$. The probability of two stars with $K = 22.5$ falling in the same resolution element, and thereby creating a blended object with $K \sim 22$, is then 0.2%. This simple calculation shows that blending is not an issue in the Maffei 1 deep field dataset.

NGC 5128 is an interesting comparison object for Maffei 1 as these galaxies have roughly similar distances (3.5 Mpc for NGC 5128 versus 4.4 Mpc for Maffei 1) and integrated brightnesses ($M_V \sim -22$); moreover, neither galaxy is in a dense environment.

Marleau et al. (2000) discuss F160W NIC2 observations of a field with a projected distance of 9 kpc from the center of NGC 5128, and in Figure 7 the H LFs from their data and the Maffei 1 deep field are compared; the population of bright foreground stars with [F110W] – [F160W] ~ 0.8 in the Marleau et al. (2000) dataset were not included in the NGC 5128 LF. The NGC 5128 data shown in this figure were shifted by 1.2 mag to account for the greater apparent distance of Maffei 1 in H assuming that $\mu_0 = 27.75$ for NGC 5128 (Marleau et al. 2000). The resulting LF was then scaled to match the stellar density in the Maffei 1 field based on the van den Bergh (1976) $V-$band surface brightness profile after correcting for the differences in distance.

There is excellent agreement between the H LFs of NGC 5128 and Maffei 1 in Figure 7. A potential concern is that the brightest stars in Maffei 1 have $H = 20.7$, whereas the brightest stars in the Marleau et al. (2000) NGC 5128 field, if viewed at the same distance and reddening as Maffei 1, have $H = 21.3$, so the peak brightness in the Marleau et al. (2000) dataset is ~ 0.6 mag fainter in M_H than in Maffei 1. However, this seeming difference in peak brightness is likely due to the relatively low stellar density in the NGC 5128 field, compounded by the modest angular coverage of NIC2. In fact, if the stellar contents in the Marleau et al. and Maffei 1 fields are identical, then scaling the deep field star counts to the projected density of the NGC 5128 field indicates that only 0.3 ± 0.2 stars between $H = 20.25$ and 20.75 would be present in the Marleau et al. (2000) dataset; hence, there is only a modest chance of detecting stars within 0.5 mag of the AGB-tip with a single NIC2 pointing at this distance from the center of NGC 5128.

5. THE CENTRAL REGIONS OF MAFFEI 1

Elliptical galaxies contain radial metallicity gradients (e.g. Davies, Sadler, & Peletier 1993; Davidge 1997), in the sense that mean metallicity drops with increasing radius. The $V-I$ color of Maffei 1 becomes bluer towards larger radii (Buta & McCall 1999), as expected if a metallicity gradient like that in other ellipticals is present. There is also a tendency for early-type galaxies in low-density environments to contain a centrally-concentrated component that is younger than the main body of the galaxy (e.g. Trager et al. 2000a). However, the tendency for $V-I$ to become redder with decreasing radius in Maffei 1 is not consistent with such a component being present. Moreover, Luppino & Tonry (1993) found that the characteristic flucuation brightness increases with radius in Maffei 1, although a similar gradient was not detected in M32 or the bulge of M31. Models by Blakeslee, Vazdekis, & Ajhar (2001) and Liu, Graham, & Charlot (2002) predict that this trend is in the opposite sense of what would be expected if a centrally-concentrated young population was present.

Is there evidence for a centrally-concentrated young component in the central field data? To answer this question, the CFHT data were analyzed with the ellipse-fitting STSDAS task ELLIPSE after the J and H images were smoothed with a Gaussian to match the angular resolution of the K data. The $K-$band surface brightness profile, plotted in the upper panel of Figure 8, follows an $r^{1/4}$ law when $\log(r) > 0$, in agreement with the profile measured by Buta & McCall (1999) at shorter wavelengths and larger radii.

The $J - K$ color profile, shown in the lower panel of Figure 8, indicates that there is a modest red nucleus, which is confined to the central $1''$ of the galaxy. The presence of a red nucleus is consistent with the $V - I$ color trend defined at much larger radii, although the apparent break in the $J - K$ profile at $r = 1''$ suggests that the central red component is distinct from the surrounding populations. If there were a central young population then one would expect to see a blue nucleus, although a large AGB component could cause an intermediate-age population to appear very red.

The $J - K$ color curve in Figure 8 is qualitatively similar to that measured by Davidge & Courteau (1999b) in M81, which contains a low-level AGN. However, there is no other evidence for an AGN in Maffei 1. Reynolds et al. (1997) detect only extended hard x-ray emission from Maffei 1, which they suggest originates from a population of low-mass x-ray binaries. If Maffei 1 contains an AGN then it must have a very modest energy output at x-ray wavelengths.

6. A SEARCH FOR BRIGHT GLOBULAR CLUSTERS

Maffei 1 is expected to host a substantial globular cluster population. With an integrated brightness of $V = 11.1$ (Buta & McCall 1999) and $A_V = 4.5$ mag and $\mu_0 = 28.2$, then $M_V = -21.6$. If the specific frequency of globular clusters in Maffei 1 is similar to that in ellipticals in small groups, where $< S_N >= 2.6 \pm 0.5$ (Harris 1991), then the Maffei 1 cluster system should consist of ~ 1130 objects.

The peak of the globular cluster LF (GCLF) in M31 occurs near $K_0 = 14.5$ (Barmby, Huchra, & Brodie 2001), which corresponds to $M_K = -10$. Therefore, adopting the M31 GCLF as a model, the peak in the Maffei 1 GCLF should occur near $K \sim 18.5$. There are a number of objects with $K \leq 18.5$ in the central field, and these are point sources in the $0\farcs35$ FWHM resolution data. The $(K, H - K)$ and $(K, J - K)$ CMDs of the bright objects in the central field are shown in Figure 9, along with the $(K, H - K)$ CMD of the DvdB background field. The sources near the center of Maffei 1 have $H - K$ colors that match those of objects having similar brightness in the background field. In addition, the sources near the center of Maffei 1 have $J - K < 1.1$, so that $(J - K)_0 < 0.3$; for comparison, Galactic globular clusters have $(J - K)_0 < 0.6$ (Brodie & Huchra 1990). Hence, the bright objects in the deep field have $(J - K)_0$ colors that are not consistent with them being old globular clusters. While young, blue globular clusters have been detected near the centers of actively star-forming ellipticals (e.g. Carlson et al. 1998), there is no evidence for recent star formation near the center of Maffei 1, so it is unlikely that a population of young clusters would be present. We thus conclude that the central 700×700 parsec of Maffei 1 is devoid of clusters brighter than the peak of the GCLF.

Could some of the bright sources in the deep field be globular clusters? Lacking $J - K$ colors for objects in this field, we investigate this issue using statistical arguements. There are 5 sources with $H - K \sim 0.2$ and $K < 19.5$ in the deep field. None of these are extended, and they have a density $\rho = 5/(14.4 \times 14.6) = 0.024$ arcsec $^{-2}$. Sources with similar brightness in the DvdB Maffei 1 and background fields have densities $\rho = 24/(34 \times 34) = 0.021$ arcsec^{-2}, and $\rho = 12/(34 \times 34) = 0.010$ arcsec $^{-2}$. The mean density of objects with $K < 19.5$ in all three fields, weighted according to field area, is then $\overline{\rho} = 0.016$ arcsec^{-2}, indicating that there should be ~ 3.3 sources with $K \leq 19.5$ in the deep field if objects of this brightness are uniformly distributed. The Poisson probability function then indicates that there is only a 12% chance that 5 objects with $K \leq 19.5$ would be detected in the deep field. These data thus hint that the deep field may contain an excess of objects with $K \leq 19.5$ when compared with larger radii.

7. DISCUSSION & SUMMARY

7.1. The Stellar Content of Maffei 1 and Other Spheroids

Deep H and K' images obtained with the UHAO + QUIRC on the Northern Gemini telescope have been used to investigate the bright AGB content of a field 3 arcmin (~ 4 kpc) from the center of Maffei 1. If it is assumed that the brightest giants in Maffei 1 have the same intrinsic $H - K$ color as late M giants in BW then a line-of-sight extinction is computed that is consistent with previous estimates, which have relied largely on the integrated properties of the galaxy.

The main result of this paper is that the infrared-bright stellar content of the Maffei 1 deep field, as gauged by (1) the brightness of the AGB-tip, (2) the shape of the AGB LF, and (3) the density of AGB stars measured with respect to surface brightnesses at visible wavelengths, does not differ significantly from that in other nearby spheroids. The

AGB-tip in the Maffei 1 deep field occurs near $M_K \sim -8.7$, and thus is comparable to the peak brightnesses in M32 (Davidge 2000a; Davidge et al. 2000), and the bulges of the Milky-Way and M31 (Davidge 2001a). Rejkuba et al. (2001) find that the peak M_K in the outer regions of NGC 5128 is ~ -8.8, which is also in remarkable agreement with the peak brightness in Maffei 1.

The near-infrared LFs of bright stars in the Maffei 1 deep field, and the outer regions of M32 and NGC 5128 are in excellent agreement. In some respects, the good agreement between the bright stellar contents of Maffei 1 and NGC 5128 is perhaps not surprising, given that these galaxies have comparable integrated brightnesses, distances, and environments. However, the chemical enrichment history of a galaxy is thought to depend on factors such as galaxy mass (e.g. Yoshii & Arimoto 1987), and it might be anticipated that the photometric properties of the brightest stars in a massive elliptical galaxy like Maffei 1 might differ from those in a smaller system like M32, due to differences in metallicity. Indeed, the integrated Mg_2 index of M32 is markedly lower than in more massive ellipticals (Burstein et al. 1984). However, the metallicity distribution function (MDF) of M32 measured by Grillmair et al. (1996) is similar to that of the outer regions of NGC 5128 (Harris & Harris 2000; Harris, Harris, & Poole 1999), suggesting that the stellar contents of M32 and larger ellipticals may not be so different.

Insight into the nature of the brightest stars in nearby spheroids can be obtained by examining their distribution within these systems. In M32 and the bulge of M31 the brightest stars are uniformly distributed throughout these systems, with a number density that scales with $r-$band surface brightness (Davidge 2000a, Davidge et al. 2000, and Davidge 2001). There are indications that the brightest stars also are uniformly distributed in NGC 5128, as Harris & Harris (2000) show that the relative number density of the brightest AGB and RGB stars does not change with radius, although it is evident from their Figures 7 and 8 that their data are not sensitive to luminous giants with solar or higher metallicities. Curiously, a comparison of the K LFs of the DvdB field and the deep field suggests that the outer regions of Maffei 1 may be deficient in stars near $K = 20.5$, suggesting that the brightest stars in Maffei 1 may not be uniformly distributed throughout the entire galaxy. A survey of the outer regions of Maffei 1, covering a square arcmin or more and sampling stars as faint as $K = 21$ would provide the data that is needed to confirm if the deficiency of bright stars in the DvdB field is real, or a statistical fluke.

Soria et al. (1996) detected stars as bright as $M_{bol} \sim -5$ in the inner halo of NGC 5128, and concluded that these objects belong to an intermediate-age population. Marleau et al. (2000) reached a similar conclusion after analyzing near-infrared observations of a portion of the Soria et al. field, and it is these data that have been compared with the

Maffei 1 deep field observations. However, peak AGB luminosity is not an ironclad means of judging the age of a population, as the peak AGB brightness is a function of metallicity as well as age, and this introduces uncertainty in the age calibration of the AGB-tip. In fact, Guarnieri, Renzini, & Ortolani (1997) examined the brightest members of moderately metal-rich globular clusters, which have old ages (e.g. Ortolani et al. 1995), and found that the brightest AGB stars have M_{bol} between –4.5 and –5.0 when [Fe/H] > -1.0; thus, the bright stars detected by Soria et al. (1996) may have ages comparable to Galactic metal-rich globular clusters.

The galaxy-to-galaxy similarity in peak M_K and steller density are difficult to explain if the brightest stars are young or of intermediate-age, as these systems must then have experienced fortuitously similar star-forming histories during intermediate epochs: not only would age and metallicity have to be tuned to produce similar peak AGB luminosities, but the intermediate-age components would also have to be uniformly distributed throughout these systems with similar spatial densities. Both of these difficulties vanish if the bright stars are old; in this case the problem of tuning the AGB-tip brightness is less acute because the rate of change of this parameter with time decreases with increasing age. Likewise, the uniform distribution of infrared-bright stars occurs naturally if they formed during the initial collapse of the system, when the main structural characteristics of the galaxies were defined and there was likely a system-wide period of star formation. Finally, stars with a peak brightness like that in Maffei 1, M32, and the bulge of M31 occur in the Galactic Bulge (Davidge 2001a), which appears to have an old age (Feltzing & Gilmore 2000; Ortolani et al. 1995).

Clearly, NGC 5128 has experienced recent star formation, with the younger populations being centrally concentrated. However, based on the comparison with Maffei 1, the main body of this galaxy is old. It thus appears that NGC 5128 is a nearby example of the 'frosting' model proposed to explain the integrated spectroscopic properties of many early-type galaxies in the field, in which a modest young or intermediate age population is superimposed on an old stellar substrate (Trager et al. 2000b).

Hierarchal models of galaxy formation, which assume that large galaxies are assembled by the accretion of smaller systems, are able to reproduce many observed properties of present-day galaxies (e.g. Somerville & Primack 1999; Cole et al. 2000). One prediction of these models is that 50% of all stars formed prior to $z = 1.5$ (Cole et al. 1994; 2000). It can be anticipated that most of the stars (or their remnants) that formed prior to $z = 1.5$ will be in spheroidal systems at the current epoch, since mergers and feedback from star formation likely prevented disks from forming until $z \sim 1$ (e.g. Weil, Eke, & Efstathiou 1998). That spheroids are dominated by stars that formed early-on is consistent with the

$\mathrm{Mg}_2 - \sigma_0$ relation of these systems, which indicates that their basic structural properties were imprinted at high redshift (Bernardi et al. 1998).

It is somewhat suprising that the brightest stars appear to be uniformly distributed throughout the main bodies of systems like M32, the bulge of M31, and NGC 5128, as the evolution of a region within a galaxy is influenced by the local mass density, which defines the escape velocity and (possibly) the star formation rate (e.g. Schmidt 1959). A radial variation in escape velocity may be the physical basis for metallicity gradients in elliptical galaxies (Franx & Illingworth 1991; Martinelli, Matteucci, & Colafrancesco 1998), as well as the tight relations between absorption line strengths and local surface brightness (Kobayashi & Arimoto 1999; Davidge & Grinder 1995). Local surface brightness is a relative measure of mass density, at least to the extent that spheroidal systems have similar M/L ratios. The surface brightnesses of the various fields that have been compared in this paper and in Davidge (2001a) are summarized in Table 1, and it is evident that these span a wide range of values. These data ostensibly suggest that the progenitors of the bright AGB stars studied in this paper can form in regions with surface brightnesses in M_V at least as low as ~ 1 mag pc^{-2} (~ 30 $M_\odot$ pc^{-2}).

7.2. The Central Regions of Maffei 1

The data presented in this paper indicate that Maffei 1 contains a red nucleus, that extends out to $\sim 1''$. The nature of this nucleus is not clear, although there are hints that it is not a low level AGN. The absence of a discrete x-ray point source in Maffei 1 has been noted by Reynolds et al. (1997). In addition, Spinrad et al. (1971) discuss the only spectroscopic observations of Maffei 1 that are known to us. Their spectrum, obtained with a $2''$ wide slit, shows strong line absorption, with no hint of central line or continuum emission.

While there is no evidence for a systematic age gradient in Maffei 1 (§5), the presence of a young nucleus can not be completely discounted. However, if the nucleus is younger than the main body of the galaxy then it must be heavily extincted and/or viewed at an evolutionary stage when the AGB dominates the infrared light. Buta & McCall (1999) do find dust north of the nucleus of Maffei 1.

As a moderately large ($M_V \sim -21.6$) elliptical galaxy, Maffei 1 should have a well-populated globular cluster system. However, the central 700×700 parsecs of Maffei 1 is devoid of globular clusters brighter than the peak of the GCLF. While dynamical evolution is expected to disrupt clusters in the central regions of galaxies (e.g. Portegies Zwart et al. 2001; Murali & Weinberg 1997; Vesperini 1997), some nearby elliptical galaxies have bright globular clusters within a few hundred parsecs of their centers. Forbes et al. (1996) investigated the central globular cluster contents of a sample of elliptical galaxies. One of the nearest galaxies in their sample is NGC 4494, which has an integrated brightness similar to Maffei 1; 6 clusters brighter than the peak of the GCLF were found within 400 parsecs of the center of this galaxy. Interestingly, despite having what appears to be a well-populated central cluster system, NGC 4494 may have a lower than average global specific cluster frequency (Larsen et al. 2001).

The specific globular cluster frequency of Maffei 1 is not known. Because of the heavy extinction at visible wavelengths any survey for globular clusters in Maffei 1 should likely be conducted in the near-infrared. Based on the relation between the globular cluster system core radius and host galaxy brightness calibrated by Forbes et al. (1996), the core radius of the Maffei 1 cluster system should be ~ 2.5 kpc, so a number of clusters should be present within ~ 2 arcmin of the galaxy center. Foreground star contamination is an obvious concern, although this does not present an insurmountable hurdle, since field stars with brightnesses comparable to those of bright clusters in Maffei 1 have relatively blue colors (§6). Hence, it should be possible to distinguish between clusters and stars using $J - K$ colors.

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Field	V Surface Brightness (mag pc^{-2})	Source
M31 Bulge Field	–2.8	Davidge (2001a)
Maffei 1 Deep Field	–1.1	This paper
Maffei 1 DvdB Field	0.3	DvdB
M32 Outer Field	1.0	Davidge (2000a)
NGC 5128 NIC2 Field	1.2	Marleau et al. (2000)

Table 1: Surface brightness measurements of fields in spheroidal systems where upper AGB stars have been resolved

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FIGURE CAPTIONS

Fig. 1.— The final K' image of the deep field, which covers $14''.6 \times 14''.4$. North is at the top, and East is to the left. The angular resolution is $0''.14$ FWHM. The bright object to the upper left of the field center is the $R = 13.4$ star GSC 03699-01165, which was the reference source for AO correction. The faint sources scattered throughout the field are stars in Maffei 1.

Fig. 2.— The final Ks image of the central field, which covers $34''.0 \times 34''.0$ arcsec. North is at the top, and East is to the left. The angular resolution is $0''.35$ FWHM. The bright source in the lower right hand corner is the $R = 12.3$ star GSC 03699-01147, which was the reference source for AO correction. The several faint point sources scattered throughout the field have $K > 18$, and are likely foreground disk stars (§6).

Fig. 3.— The mean K' light profiles of stars in two radial intervals in the Maffei 1 deep field. The solid line shows the PSF for stars within $5''.1$ of the AO guide star, while the dashed line shows the PSF for stars with $r \geq 5''.1$; these radial intervals sample comparable areas in the Maffei 1 deep field. The curves were constructed from stars having similar brightnesses so as not to bias the comparison towards a particular radius. Note the excellent agreement between the two curves, indicating that the PSF is stable across the field.

Fig. 4.— The $(K, H - K)$ CMD of the Maffei 1 deep field. Stars in Maffei 1 form the broad plume with $K < 20$ centered near $H - K = 0.7$. The majority of sources with $K < 19.5$ are likely foreground stars in the Galactic disk. The error bars show the $1-\sigma$ uncertainties predicted from the artificial star experiments, while the dashed line shows the 50% completeness level.

Fig. 5.— The K LF of the Maffei 1 deep field. $n_{0.5}$ is the number of stars per square arcsec per 0.5 mag interval in K. The solid line shows the raw LF constructed from stars detected in both H and K', while the dashed line is the LF corrected for incompleteness. The error bars include counting statistics and the uncertainities in the completeness corrections. Also shown in the lower panel is a power-law fit to the completeness-corrected LF when $K > 20.25$, which has an exponent $x = 0.70 \pm 0.07$.

Fig. 6.— The K LF of the Maffei 1 deep field compared with the K LF of the field studied by DvdB (upper panel) and the M32 outer field observed by Davidge (2000a) (lower panel). The LFs in this figure have been corrected for incompleteness, and the errorbars show the uncertainties due to counting statistics and the completeness corrections. $n_{0.5}$ is the number of stars per 0.5 mag per square arcsec in the deep field. The M32 and Maffei 1 DvdB LFs were shifted along the vertical axis to match the stellar density in the Maffei 1 deep field using

the published surface brightness profiles given in the text, while the brightnesses of stars in M32 have been shifted to match the distance and reddening of Maffei 1. The errorbar in the upper left hand corner of the lower panel shows the combined systematic uncertainty in the relative distances and reddenings of M32 and Maffei 1; note that this error is comparable to the offset between the M32 and Maffei 1 LFs.

Fig. 7.— The H LFs of the Maffei 1 deep field (solid line) and the Marleau et al. (2000) NGC 5128 field (dashed line). The brightnesses of stars in NGC 5128 were shifted to match the distance and reddening of Maffei 1 prior to constructing the LF for this galaxy, and the result was then scaled along the vertical axis to match the stellar density in the Maffei 1 field using published surface brightness measurements. The errorbars show the uncertainties due to counting statistics and the completeness corrections; $n_{0.5}$ is the number of stars per 0.5 mag interval in H per square arcsec in the Maffei 1 deep field. Note the excellent agreement between the LFs of these galaxies.

Fig. 8.— The $K-$band surface brightness and $J - K$ color profiles near the center of Maffei 1. r is the distance in arcsec from the galaxy center, and the dotted line indicates 0.35 arcsec, which is the angular resolution of these data. Note the appearance of a red nucleus when $r < 1''$.

Fig. 9.— The $(K, H - K)$ and $(K, J - K)$ CMDs of sources with $K < 18.5$ in the Maffei 1 central field. Sources in the DvdB background field are plotted as open squares in the $(K, H - K)$ CMD. Note the excellent agreement between the central and background field datapoints on the $(K, H - K)$ CMD.